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PROTECTION FROM DAMAGE BY FROST

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Introduction[1]. Although the great physical processes controlling the weather are not subject to modification by man, meteorology is pointing out ways in which some of the results of weather conditions may be avoided. A notable instance of the economic importance of meteorological study is to be found in the diminution of frost damage, which was formerly regarded as an unavoidable misfortune to be borne at more or less frequent intervals, even though greenhouses and a paper covering for small gardens had long been known. These small-scale experiments, however, had little influence on the solution of the great economic problem of protecting commercial crops from frost damage until climatologists began to study the related physical principles.

Investigations of frost damage and the weather conditions which give rise to frost have shown that its occurrence can generally be forecast and that the prevention of damage is possible. Even where complete protection fails, the damage is greatly lessened. Frost damage is in many cases the result of neglect.

Conditions of Frost Occurrence. There are three classes of damaging low temperatures: (1) hoar frost, in which the temperature of the air near the surface of the earth is below the dew point and the dew point is below 273°A (32°F); (2) "black frost," or "dry freeze," in which the temperature of the air near the surface of the earth falls below 273°A under local radiation and the dew point is not reached; and (3) "general freeze," when the air is thoroughly mixed and the whole mass is below 273°A.[2] With hoar frost and dry freeze inversions of temperature are the rule; this is not the case with the general freeze. As the general freeze occurs at times when plant activity is suspended, that is during the winter, it is of little economic importance. The amount of air involved makes protective measures impracticable and the condition is not properly a part of the frost problem.

Both hoar frost and dry freezes are the result of strong local cooling under a clear sky; the earth, losing heat rapidly to space, becomes very cold and the air lying on it is chilled. The cold air remains in the lower places so that frost damage is apt to be intensified in the valleys.[3] The low temperatures are a result of local cooling, but the general meteorological conditions control the possibility of such cooling. The controls vary in different parts of the country, but frost conditions are associated with anticyclones; the air then has a low relative humidity and the sky is clear. Hoar or black frost cannot occur with even a moderate wind, as wind tends to mix the air, thus preventing the intense cooling near the earth.

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[1] A selected bibliography on frost in the United States by Cora L. Feldkamp and the writer is published in the *Monthly Weather Rev.*, Vol. 43, 1915, pp. 512-517. This bibliography is intended to cover the subject adequately, but in general earlier titles have not been repeated where later papers cover substantially the same ground.—On the same topic as this paper, see also the item on p. 146.

[2] A. E. Beals: Forecasting Frost in the North Pacific States, *U. S. Weather Bur. Bull. 41*, p. 41, Washington, 1912.

Frost Damage. Frost damage is the result of low temperature only; the appearance of crystals is merely an indicator of the temperature. "Low temperature congeals the watery part of the cell sap and also the intercellular water content of the plant. Within certain limits this may or may not be injurious, provided the protoplasmic contents of the cell are able to absorb the water and do this before the cell structure collapses as a result of insufficient cell turgor. Frequently the frosting of plants is followed by a sudden rising of temperature, in which case the water which was part of the cell sap in the normal condition of the plant escapes through the cell wall into intercellular spaces, or even from the plant entirely, and thus the protoplasm of the cell, being unable to assume its normal condition, becomes disorganized and decomposition follows."[4] Frost damage may be prevented by keeping the temperature above the freezing point of the plant juice, and also in many cases by preventing rapid warming after freezing. The heat released by the condensation of moisture tends to make hoar frost less dangerous than low temperatures in which condensation does not occur, because condensation checks further cooling.[5]

Methods of Protection. Methods of protection against frost damage may be classified according to the physical principles involved, although most of the commercial methods are based on combinations of these principles. It should be noted that the cost of protection is a very important factor in the commercial application of protection. It is not practicable to protect at a cost greater than the value of the crop, unless this is necessary to save trees. The cost of protection is properly insurance, and the profits must be sufficient to carry this cost if protection is to be commercially possible. In general, only crops demanding very intensive methods of cultivation, such as fruit and vegetables, are able to bear this charge.

Protection from frost damage is based on the prevention of freezing temperatures or on the protection of frosted plants from too rapid warming. The preventive measures are safer, as the protection of the frosted plants is essentially an attempt to help the plant recover from

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[3] C. F. Marvin: Air Drainage Explained, *Monthly Weather Rev.*, Vol. 42, 1914, pp. 583-585; A. G. McAdie: Temperature Inversions in Relation to Frosts, *Annals Harvard College Observ.*, Vol. 73, pp. 168-177, Cambridge, 1915.

[4] E. R. Lake: Action in Plant Life When Subjected to Frost, *U. S. Weather Bur. Climate and Crop Service, Oregon Section*, Vol. 6, No. 7, p. 3, Portland, 1900.

[5] See "Latent heat" in any good text on physics.

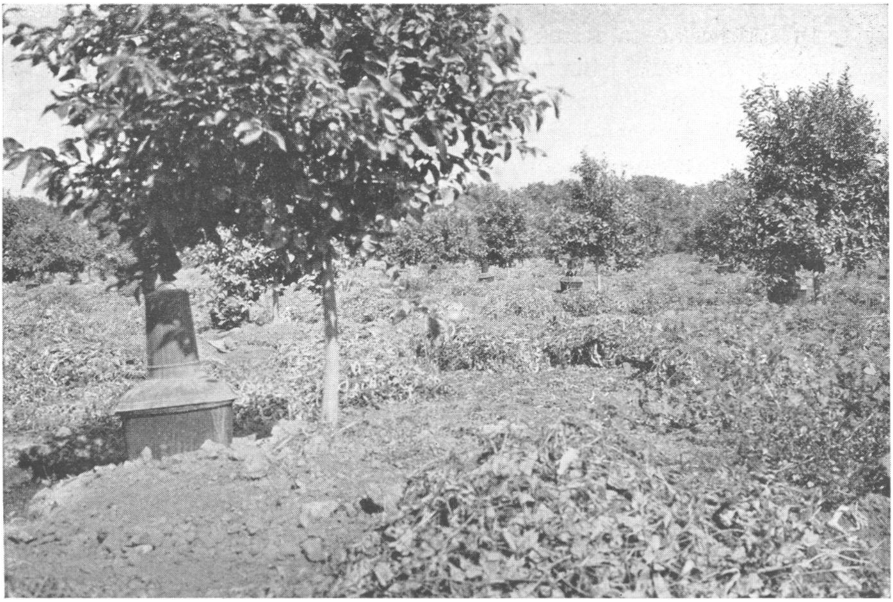

FIG. 1.

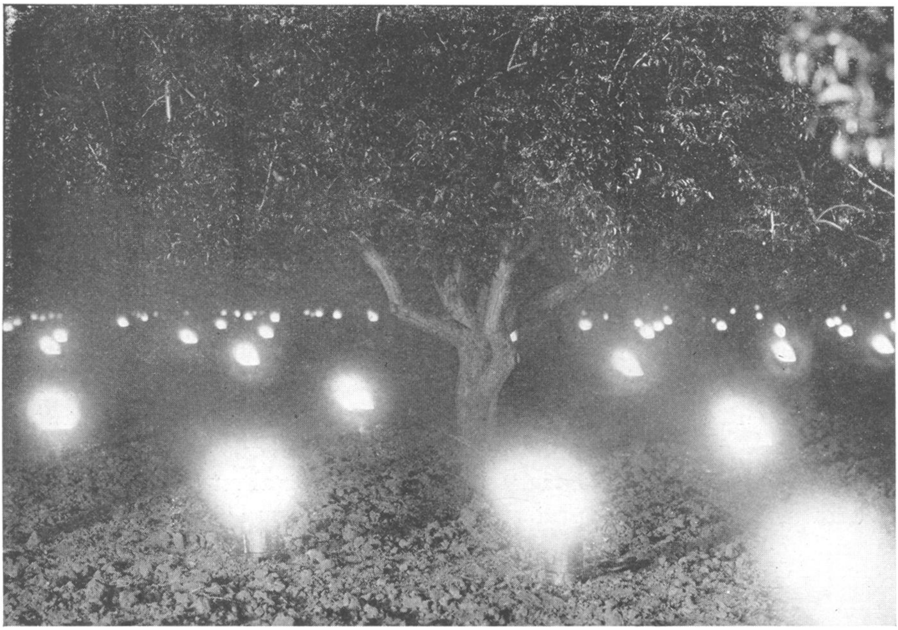

FIG. 2.

FIG. 1—Oil pots in a lemon orchard, Santa Paula, southern California. (Photo by Ford A. Carpenter, Sept. 30, 1915.)

The pots are placed one or more to a tree. They hold seven gallons each and burn crude oil in amounts depending on the heat required.

FIG. 2—Oil pots in use at Medford, Oregon. (Photo furnished by the Medford Commercial Club.)

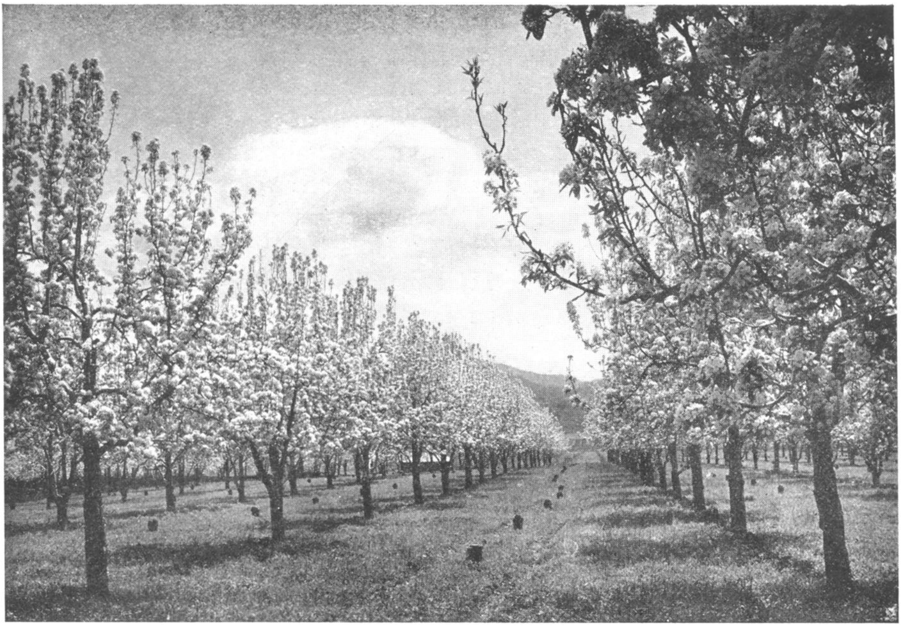

FIG. 3.

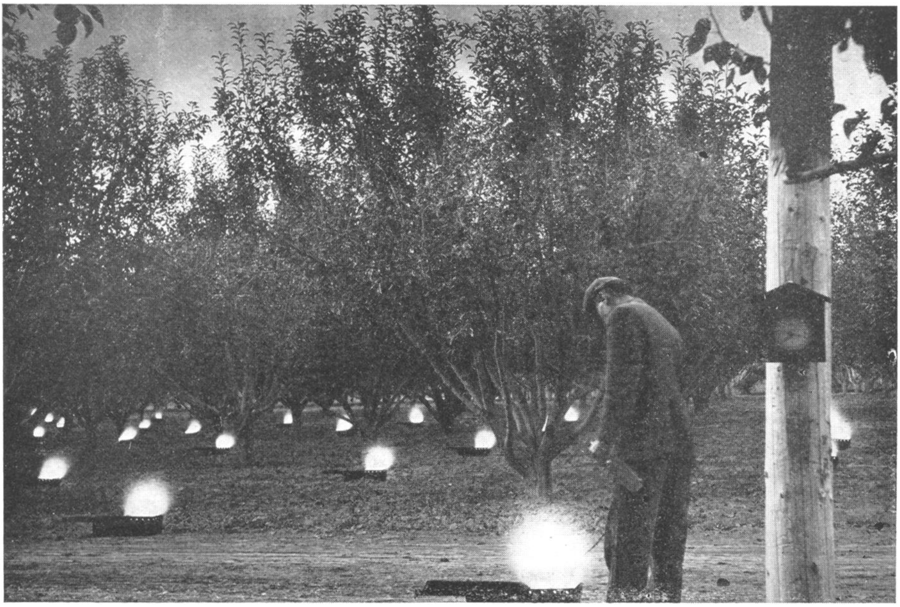

FIG. 4.

FIG. 3—Oil pots in place in an orchard at Medford, Oregon. (Photo furnished by the Medford Commercial Club.)

FIG. 4—Hamilton type of orchard heater in operation at Grand Junction, Colorado. (Photo by Frank E. Dean.)

frost damage. Temperatures may be held above the danger point by adding heat to the lower air, by checking terrestrial radiation, or by mixing the air to bring larger amounts in contact with the cooling earth.

Addition of Heat. The simplest method of preventing dangerously low temperatures is to supply heat to the lower air in amounts sufficient to make up for the loss to space. This method is wasteful because of the rapid radiation of heat to space; but it has met with considerable favor, and, combined with the checking of radiation, seems to be the most successful commercial method. Heat may be added by fires, by steam in pipes, by hot water in irrigation ditches,[6] and probably by the use of electrical energy.

Heating by small fires is the most practicable; the fires must not be large enough to scorch the plants or to start a convectional circulation; one fire to each tree is the best practice in fruit orchards. The fuel used is determined by the cost, oil in California, wood in Oregon. In spite of the effort to get "clean burning" fires, it is to be noted that smoke by checking radiation makes the demand for heat less severe.

Other methods of heating are far less common because they are more expensive and less flexible. Steam pipes are limited by great initial cost, besides having a fuel charge equal to fires; they are not especially effective, as radiation is not checked. The use of a flow of hot water in irrigating ditches is limited by the scarcity of water in most fruit districts, by the cost of heating, by the danger of injury to some trees by hot water, and by the tendency of irrigation to start new growth susceptible to frost damage. The use of water increases the humidity and, therefore, belongs in part to the third method. Electricity, as the most easily transported type of energy, offers interesting possibilities. The time when protection is needed, the early morning hours, is a time when the demand for power is small, but the power plants have to run. It is almost certain that some method will be devised to utilize electricity to supply the heat lost by the lower air.

Checking Terrestrial Radiation. Theoretically the best means of preventing low temperatures should be the checking of the loss of heat by radiation. If the heat loss can be prevented, the temperature will not fall to a dangerous point under hoar frost and dry freeze conditions. The loss of heat may be checked by introducing between the earth and the sky a roof of poor radiating material. Paper coverings over gardens are a type of this protection; the greenhouse is another. Lath screens form a very acceptable roof, even though covering only fifty per cent of the sky. The cost of covers is the greatest objection; all covers and roofs, except those of glass, must be removed for the plants to get sunshine, although lath roofs may be arranged with the laths north and south, so that the noonday sun is fairly strong but there is shading in the early morning.

Artificial clouds form another type of covering. A cloud cover, natural or artificial, is very effective in checking radiation. Smoke clouds are usual for protecting against frost, but there is generally a good deal of steam in the smoke. Under frost conditions the humidity is often so low that water in the clouds is rapidly evaporated and does not persist long enough to be of much use unless continually renewed. The clouds of combined smoke and stream are usually formed by burning wet straw or refuse; the usual oil fire also makes a heavy smoke which forms an effective cloud. Even very moderate winds have a tendency to carry the clouds away from the region, so that a continued supply of smoke is essential, although winds during frost conditions are always light. The development of a fine mist over the area to be protected is closely related to cloud formation. This is usually accomplished by the spray system of irrigation; devices similar to lawn sprinklers above the area have also been used. In addition to the mist formed, the evaporation of the water increases the humidity and checks radiation by the third method.

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[6] See *Increased Humidity*, below.

Increased Humidity. Any means of rendering the air less diathermanous will check radiation; in practice this is limited to the increase of the vapor content by the evaporation of water in the area to be protected. Water vapor is practically opaque to the longer waves of heat, such as those radiated from the earth; and when it is present in sufficient quantities, cooling must take place by the slow process of conduction from earth to water vapor and outward through the vapor from particle to particle, instead of by direct radiation from the ground to space. The vapor content of the air may be increased by the evaporation of water by heat; it is not necessary to boil the water, as a very slight increase in temperature will cause rapid evaporation. Another method is to supply heated water to the irrigation ditches. Both are expensive and little used, but it is possible that a small unit may be developed in connection with the use of oil pots, a unit to a tree. Sprays of water or steam also tend to increase the humidity; steam is better than water because of the higher temperature and also because of the smaller drops. The spray method gets the water directly into the air by evaporation.

The presence of water on the ground increases the humidity but not as much as steam or spray. Water in the irrigation ditches also increases the humidity, but irrigation is not regarded as good practice because of the difficulty of obtaining water, because of the tendency for new growth to start, and because wet ground makes passage through the orchard difficult when it is essential that the whole area should be readily accessible. In cranberry marshes protection by flooding is common, the plants being covered with water. Besides increasing the humidity, water on the surface of the ground decreases the effectiveness of terrestrial radiation, because water is about twice as hard to cool as dry land and a greater heat loss is required to produce the same temperature.

Mixing the Air. The only means of mixing the air on a large scale is

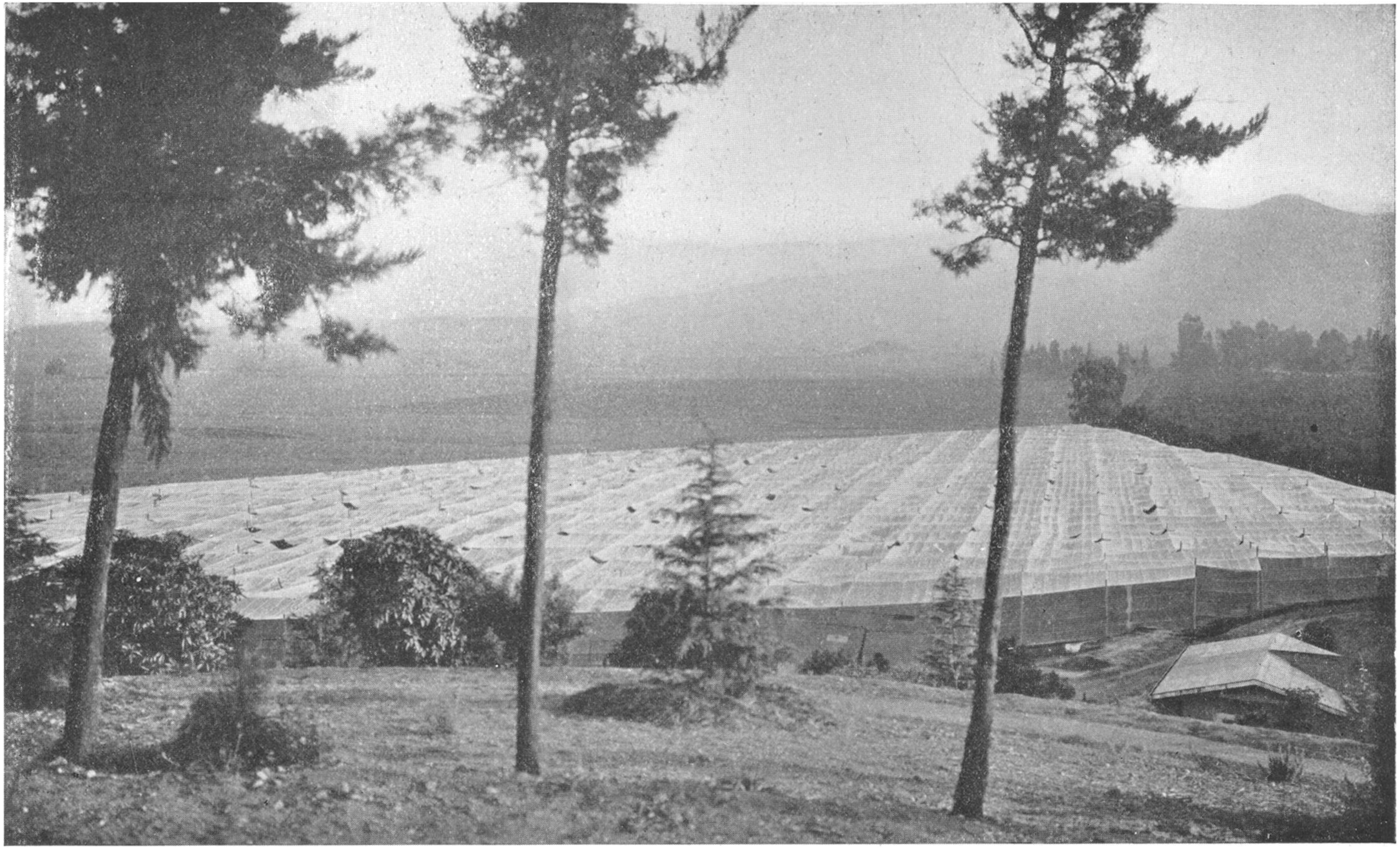

FIG. 5—Five-acre lemon grove at Corona, California, covered with "tobacco cloth". (Photo by Ford A. Carpenter, Sept. 30, 1915.) The covering is of advantage during hot summer days but screens the sun too much in winter. Radiation is checked 4° to 6° in winter.

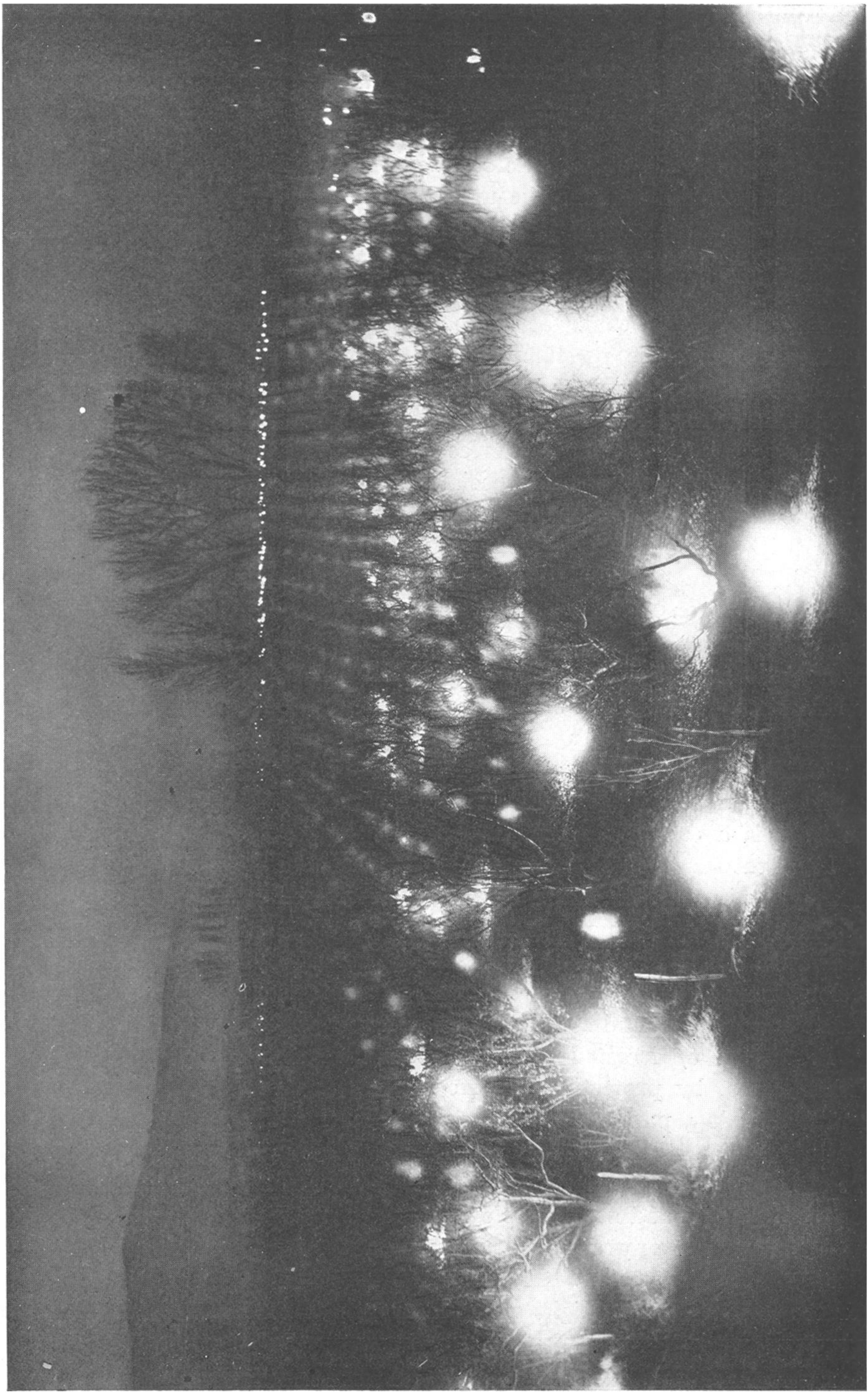

FIG. 6—Oil pots in operation at Grand Junction, Colorado. (Photo by Frank E. Dean.)

the wind; very little has been accomplished by man in this direction. Damage by cold winds has been prevented by the erection of wind-breaks, but as frost damage usually occurs in the absence of wind they are of little value. In directing feeble air currents to prevent the accumulation of cold air in "frost holes," wind-breaks may be of some value, but it is necessary to use great caution or the "holes" will be increased in area or intensity.

During frost conditions the upper air is relatively warm; it is a thin layer lying on the earth which is cooled to a dangerous temperature. If the air could be mixed so that the heat lost to the cooling earth could be supplied from a greater thickness of air, the surface layer would not become dangerously cold. It has been suggested that stirring the air by mechanical means is possible and that some device may be discovered which will draw the warmer air from aloft before the air near the earth is excessively cooled.[7] At present there is no such device nor is there any indication of how such a device can be obtained. It is quite possible that some type of machine, especially some electrical apparatus may be made to do this work; but the direct application of heat to the cooling earth without the intervention of mechanical devices seems a better method. Mixing the air has not become a practicable method of preventing frost damage.

Combinations. Many of the methods of protection in commercial use involve more than one of the foregoing physical principles. The most common method is that of small fires, which in practice give a considerable amount of smoke, even under the conditions of cleanest burning. The protection obtained is the result of the partial checking of radiation and the heating of the air to make up for the energy lost to space. Heat and moisture is a combination which depends on decreased diathermancy as well as heat supply. In most cases protection based on a single physical principle is inadequate, either because of the excessive protection necessary, smokeless heat requiring considerable heat to supply the loss through the clear dry air, or because of the necessity of perfect protection (for example, a cloud must be very dense to prevent much loss of radiation by leakage and to keep the ground above a dangerous temperature).

Protection of Frosted Plants. Frost damage may be prevented, or rather cured, by protecting the frosted plants from too rapid warming. Rapid warming, particularly by sunshine, causes the frozen water of the sap to melt near the surface of the plant or fruit while in the deeper parts the sap is still frozen; the result is that the outer cells are cut off from the source of supply and are not able to survive. Slow "defrosting" throughout the whole structure may be brought about by protecting the frosted plant while it is warming. Of course, the plant must not have been frosted for too long a time. Bright warm mornings characteristically follow the clear nights upon which frost occurs because radiant heat from even the low sun finds little difficulty in passing through the clear air.

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[7] There are, of course, very serious complications here, for adiabatic warming and cooling and adiabatic stability are involved, to say nothing of the mechanical difficulties of moving large masses of air.

Rapid warming may be prevented by shading the plants by covers or clouds. When covers are used for protection they are not removed until the danger from warming has passed; lath roofs are arranged with the laths north and south so that as the sun gets higher a smaller amount is cut off by the laths. In the absence of wind artificial clouds tend to remain well into the morning. These methods of preventing warming are also those used to check radiation; and the evil effects of frosting which are the result of imperfect protection may be prevented by the morning shading.

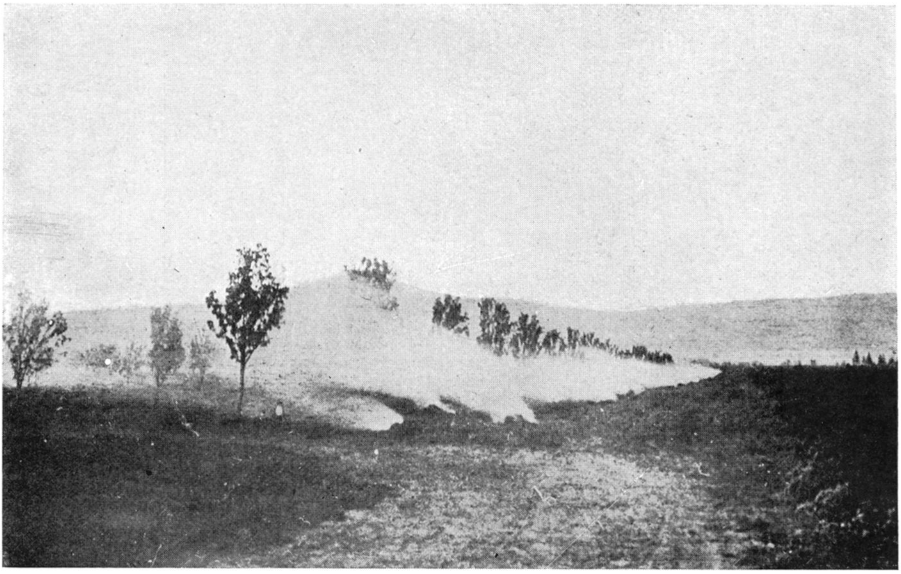

FIG. 7—Smudging in the Hollywood Orchard at Medford, Oregon. (Photo furnished by P. J. O'Gara and plate loaned by author.)

Too rapid warming may also be prevented by spraying the plants with water at a temperature of about 273°A just before sunrise. The coating of ice formed must be melted before warming can begin, and probably the energy set free by the freezing water is of some importance. The ice is said not to injure blossoms or fruit. It is, however, far better practice to prevent frosting.

Frost Forecasting. Protection against frost damage depends upon the early receipt of accurate forecasts. Weather-map studies have shown that frost is associated with definite weather types, and general forecasts of conditions favorable to frost formation are made on the basis of pressure distribution. These general forecasts are transmitted rapidly to the regions concerned, where they are applied by trained local forecasters each familiar with his region. Local forecasting of probable minimum temperatures has met with varied success. The older idea, which at first sight appears sound, that the dew point in the late afternoon is approximately the minimum temperature of the following morning, has proved too unreliable for practical use, although in some cases the dew point method has been successful.[8] Cox has found that soil temperatures seem to exert a considerable control over the occurrence of frost,[9] but the study has not yet progressed far enough to give quantitative results. Frost forecasts may be verified by the occurrence of frost or frost damage or by the occurrence of minimum temperatures of 273°A or lower with a clear sky. The temperature of the plants is several degrees lower than that shown by thermometers in standard shelters when the sky is clear, but the temperature required to damage plants is about the same amount below 273°A as this difference. Carpenter has found that in the vicinity of Los Angeles

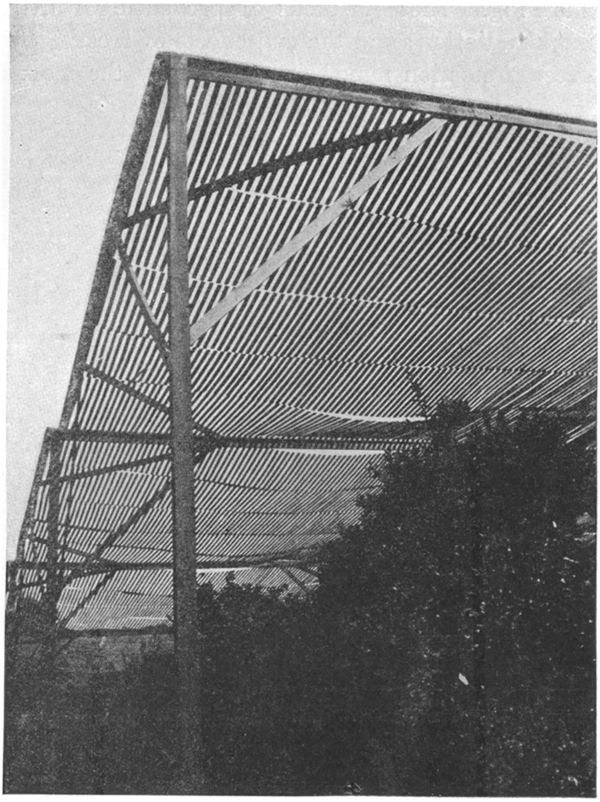

FIG. 8—Lath screen at ranch of A. J. Everest, Riverside, California. (Plate furnished by U. S. Weather Bureau.)

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[8] J. W. Smith: Frost Warnings and Orchard Heating in Ohio, *Monthly Weather Rev.*, Vol. 42, 1914, pp. 578-583; reference on pp. 579-580.

[9] H. J. Cox: Frost and Temperature Conditions in the Cranberry Marshes of Wisconsin, *U. S. Weather Bur. Bull. T*, p. 118, Washington, 1910.

a piece of bright tin freely exposed to the sky is a more constant indicator of hoar frost—not of black frost—than the vegetation; frost crystals on the tin correspond to temperature and moisture conditions giving frost. It is not possible to use temperatures at the ground or of the vegetation because of the difficulty of obtaining such temperatures and also because of the great local variation.

The final application of the forecast must be made by each grower for his own area. An exact knowledge of the spots most subject to low temperatures is of great assistance, as thermometer readings in these places will indicate when protection is necessary, especially as it is a great deal easier to prevent the temperature from falling than it is to raise it from a dangerous point. The temperatures of the coldest places will show the danger before the rest of the region is too cold, if the thermometers are read frequently during nights upon which frost is possible.

Frost Fighting. A considerable portion of the work of frost fighting has been accomplished when the campaign is planned. Fruit growers and others who have plants to protect should be fully prepared before the beginning of the season of possible danger. By this time, if fires are to be used, fuel should be on hand, the position of each fire located (oil pots in place), and the necessary labor arranged for. A definite plan of action should be prepared so that the receipt of a frost warning will set in motion an unhurried series of preparations. It is generally advisable to use the means of protection which has been found satisfactory in the region, although experiments with other methods should not be discouraged. In the case of heating and of cloud formation it is especially desirable that the same methods be used throughout whole areas, as co-operation makes the work of the individual, particularly if he is not on the edge of the district, much more effective.

Summary and Conclusion. Frost damage is the result of low temperatures due to intense local radiation at a time when the tree is unprepared to withstand the cold. It usually occurs on clear, quiet nights under anticyclonic conditions. The low temperatures can be prevented by heating the lower air to supply the loss of heat to the cold earth and by checking radiation from the earth; mixing the air is not now practicable. The methods most successful commercially depend upon the combination of heat and smoke. The best practice is fairly clean-burning small fires one to each one or two trees. Protection of frosted plants from too rapid warming often prevents damage, but there is the danger that the plants may have been too long or too severely frosted to permit recovery.

Protection from frost damage is often quite possible, if effective use is made of the information and warnings issued by the U. S. Weather Bureau. Effective protection requires some knowledge of the nature of frost damage and of the conditions under which frost occurs. A knowledge of the region, especially of the seasons of frost and of the places of lowest temperature, is also essential. The methods of protection should be studied, and the type which has proved successful in the particular region or in one where the conditions are similar should be selected. The campaign should be carefully planned in advance. Successful frost fighting depends upon co-operation by the whole community so that the campaign may be conducted intelligently and without duplication of effort; arrangements should be made for the immediate receipt of frost forecasts from the nearest office of the Weather Bureau. In the elimination of loss from frost damage alone the total expenditure for meteorology in the United States has been saved many times over. Frost damage occurs largely, if not wholly, in cases where the proper precautions have been neglected or ignored.